IOP Conference Series: Earth and Environmental Science

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To cite this article: J Zanni *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **290** 012140

IOP Conf. Series: Earth and Environmental Science **290** (2019) 012140 doi:10.1088/1755-1315/290/1/012140

Incremental Integrated Holistic Rehabilitation: A New Concept to Boost a Deep Renovation of the Existing Building Stock

J Zanni[1], S Labò[1], C Passoni[1], E Casprini[1], A Marini[1], A Belleri[1] and C Menna[2]

[1] Department of Engineering and Applied Science, University of Bergamo, via Marconi 5, 24044, Dalmine (BG), Italy

[2] Department of Structures for Engineering and Architecture, University of Naples Federico II, via Claudio 21, 80125, Napoli (NA), Italy

jacopo.zanni@unibg.it

Abstract. The renovation of the post-World-War-II reinforced concrete building has become an urgent action in order to meet energy-saving and to foster safety among the European communities. In this context, in order to overcome the major barriers to the renovation and to increase the feasibility of a deep, sustainable renovation action, a new incremental holistic rehabilitation (IHR) approach is introduced. This new approach has the major aim of fostering a safe, resilient and more sustainable society by addressing the life cycle thinking principles and by implementing incremental levels of safety. In this paper, an IHR strategy is defined and applied to a reference scholastic building. Fundamental criteria for the selection of the proper renovation strategy guaranteeing the minimum environmental impact and the applicability to Reinforce Concrete existing infilled frames are derived. The results show that a holistic incremental rehabilitation strategy can represent a good answer to the urgent need of sustainable renovation of Italian and European building stock.

1. Introduction

The obsolescence of the European existing building stock requires a great renovation effort in order to reach the ambitious EU targets in terms of sustainability, safety, and resilience. Despite such a critical scenario, to date, the renovation rate is only equal to 1% [1]. To effectively foster sustainability, such a rate must be boosted by understanding, and removing, the barriers to the renovation. The Building Performance Institute Europe (BPIE) identified as **major barriers**: the need to relocate the inhabitants (or, in general, the activities in case of non-residential building), the extended downtime during the construction works, the high costs of the interventions, and the lack of adequate business models fostering the renovation [1–3].

To overcome such barriers, a holistic sustainable retrofit from the outside of the existing buildings under a Life Cycle Perspective has been recently introduced [4]. The term holistic retrofit refers to an approach that concurrently tackles all the building deficiencies, increasing the structural service life while pursuing safety, sustainability, and resilience. Integrated renovation techniques mitigate the barriers connected to costs and duration of the works. They require a single construction site for architectural, energy and structural renovation, with the added benefit that some of the components may serve multiple purposes. In addition, the structural intervention may be financed by the savings obtained with the energy efficiency improvements. In order to avoid the relocation of the inhabitants and the existing building downtime, interventions exclusively operated from the outside of the building may be adopted. Finally, as to ensure the sustainability of the intervention, a new Life Cycle Perspective [5] may be embraced in order to minimize environmental and economic impacts and losses along the whole Life Cycle of the retrofitted building.

Only recently, an innovative business model has also been introduced to increase the feasibility of the renovation projects. When the retrofit intervention is too demanding from an economic point of view, the renovation works may be split into different steps distributed over time, which allow the building to reach increasing levels of performance. This procedure is called Incremental Rehabilitation. In this paper, focus is made on Incremental Seismic Rehabilitation (ISR) [6] and a novel concept of minimum safety intervention is discussed. The proposed method is then applied with reference to an Italian school, which is representative of the post-WWII RC building stock.

2. Incremental seismic rehabilitation

The Incremental Seismic Rehabilitation (ISR) has been already envisioned in the USA since the end of last century when some scientific research institutes and the Federal Emergency Management Agency (FEMA) developed the guidelines for the application of the ISR to the existing building stock [6].

The ISR integrates an ordered series of discrete actions into ongoing facility maintenance over an extended period of time. Each incremental rehabilitation step must provide a positive contribution to the structural behavior without leaving the building worse than before. The main concept is that *incremental improvement is better than delayed improvement or no improvement at all, and that seismic retrofit would occur more frequently in existing buildings if initial costs and functional disruption could be reduced* [6] (Figure 1).

In Figure 1, by expressing the structural benefits as a percentage of the benefits achieved by a full seismic rehabilitation conducted in year zero, the life-cycle benefit analyses of an incremental rehabilitation project are plotted. It can be observed that the benefits of an incremental seismic rehabilitation project are, in the end, almost as much as many of a single-step rehabilitation project but delaying the construction costs.

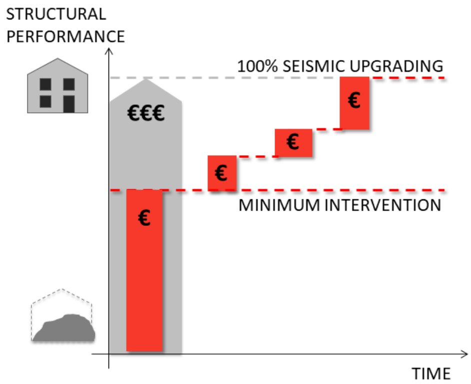

Figure 1. Concept of ISR and minimum intervention [7].

Since the rehabilitation works will be staged over an extended period of time, some rehabilitation measures can be implemented sooner and others later, thus allowing the integration of the structural retrofit measures into ongoing facility maintenance projects that are routinely scheduled during the building lifetime, so reducing the initial costs and the disruption connected to the construction works.

The guidelines suggest that the interventions should be organized according to structural priority, use priority or integration priority with other programmed maintenance interventions. In this research, structural priority earns higher relevance, considering that the renovation of the existing building should first avoid human lives and material losses. Following this philosophy, the new concept of **minimum intervention** may thus be introduced, which is the one able to guarantee a minimum level of safety for the inhabitants during a seismic event [7]. By introducing the minimum intervention, ISR would allow reaching, even with the first step, a minimum level of safety, thus avoiding structural collapse and losses of human lives after a seismic event. With such an approach, the life safety level in the existing buildings could be reached in a short time and avoiding high costs. Higher safety levels and other aspects of the renovation could be completed in a longer period by planning other incremental rehabilitation steps.

ISR represents a winning strategy especially for large-size structures or for those structures that many people use in daily life, like public services as health and education or workplaces. For those structures, single-stage retrofit interventions would require a very long time and a large capital investment, which often represent an insurmountable barrier. In addition, this strategy is optimal for those building typologies that have limited period of inactivity, which may be exploited for retrofit works. As an example, some building typologies suitable to be renovated through this innovative approach are:

- Hotels and tourist establishment, where interventions can be planned during low season periods;
- Hospitals, where interventions can be subdivided into specific areas so as not to hinder the functionality of the remaining departments;
- Office buildings, exploiting summer and holiday closure;
- Industrial buildings, where through a few local interventions, which can be realized during the short period of inactivity, the seismic risk can be considerably reduced;
- School buildings, exploiting summer and holiday closure.

3. Application to a reference scholastic building

In this section, the ISR principles previously introduced are applied to a reference school building located in Brescia (Northern Italy). For the reference case building typology, the need to relocate the activities represents the major barrier to the renovation (1st barrier for the reference case); thanks to quite long closure periods during the summer holidays, it has been possible to plan important ISR interventions [8]. Moreover, an effective ISR plan allow integrating the structural interventions with other works, often necessary, of energy efficiency and technological improvement thus reducing the construction time and costs (2nd and 3rd barriers for the reference case). To reduce the initial costs (4th barrier for the reference case) while guaranteeing a minimum level of safety at an early stage, a minimum intervention target was introduced in the ISR plan.

3.1. Description of the building

The school, built in 1966, is a four-story RC structure developed on a basement 0.80 m high. The result is an irregular building featuring an inter-story height of 0.80 m at the ground floor and 3.52 m at the upper floors. The structural layout, reported in Figure 2a, features three one-way longitudinal frames in the *y*-direction, and five one-way longitudinal frames in the *x*-direction. The span dimensions are variable, but in general, the beams feature very low length-height ratios. The beams structural details were obtained from the simulated design considering only the vertical loads (Figure 2b).

As the columns are concerned, each section is reinforced with corner steel rebar and single stirrups Φ6/15 cm (Figure 2b). The steel rebar dimensions are equal for all the columns at the same floor, while they decrease over the height of the existing building (from 2+2 Φ20 at the basement, ground floor, and first floor, to 2+2 Φ16 at the second floor, and 2+2 Φ12 at the third floor).

The staircase core is made of two RC walls not conceived to withstand the horizontal loads. The infill panels are regular over the height of the existing building and consist of a double layer of hollow bricks with an air gap, for a total thickness of 30 cm.

The structural materials are concrete C20/25 and steel AQ42. The design spectrum used for the analysis is an elastic spectrum related to the horizontal component of the seismic action at the Life Safety Limit State (LSLS), referred to a soil category D and topography T1, (a_g=0.168g) according to the Italian Building Code [9].

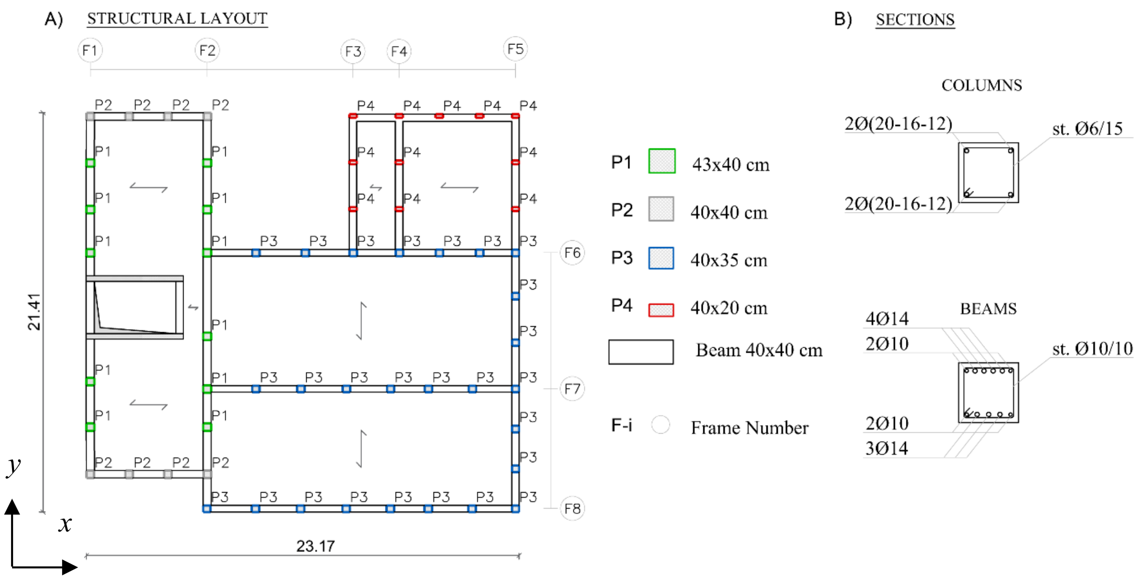

Figure 2. a) Structural layout and section type for the reference building, b) Beam and column sections. In the column section, the progressive reduction of the steel rebars diameters is reported.

3.2. *Structural analysis*

The building was modeled as a three-dimensional structure with the software Midas GEN [10].

The frame elements were modeled as beam elements fixed at the base and the non-linear behavior was accounted for by means of lumped plastic hinges calculated according to the Italian Building Code [9]. The flexural resistance was modeled by introducing the FEMA plastic hinges considering, for the columns, the interaction between the bending moment and the axial force; the shear behavior, indeed, was assumed to be elastic up to the ultimate capacity and, beyond that limit, the curve decays quickly thus exhibiting a sudden brittle failure. Floors were considered as rigid diaphragms.

The infill panels were modeled by means of truss elements converging in the beam-column joints. The non-linear properties of these elements were described by means of a trilinear force-drift curve in which the cracking and the peak forces (on the *y*-axis) were evaluated according to the Decanini Model [12], while the cracking and the peak drifts were introduced in accordance to the traditional values of 0.3% drift for minor cracking in the infill panels, and 0.5% drift for the infill failure [13]. Since the staircase walls were not conceived for the horizontal loads, they were modeled as stiff elements with low ductility. The mechanical properties of the structural materials were corrected with a confidence factor equal to 1.2.

Once the Finite Element Model was defined, non-linear static analysis (pushover – PO) were carried out. The evolution of the inelastic behavior of the existing structure was then described highlighting the possible collapse mechanism and the existing building vulnerabilities. Subsequently, the displacement demand was calculated considering the elastic spectrum at the LSLS [10].

For both the directions of the existing building, the pushover curves showed the same behavior; for this reason, only the capacity curve of the existing building in the *x*-direction is here discussed (Figure 3). As shown in Figure 3, the existing building does not satisfy the displacement demand at the LSLS and two significant vulnerabilities are highlighted: 1) the shear collapse of the beams in the frame F7 which can cause the local collapses of some structural elements and the bending failure of the adjacent columns, and 2) the shear failure of the columns at the basement featuring a soft-story mechanism providing the collapse of the existing building.

The collapse mechanism highlighted by the pushover analysis was expected due to the high vertical irregularity of the structure, while the beam shear collapse could be attributed to the very low ratio between the length and the height of the beam elements.

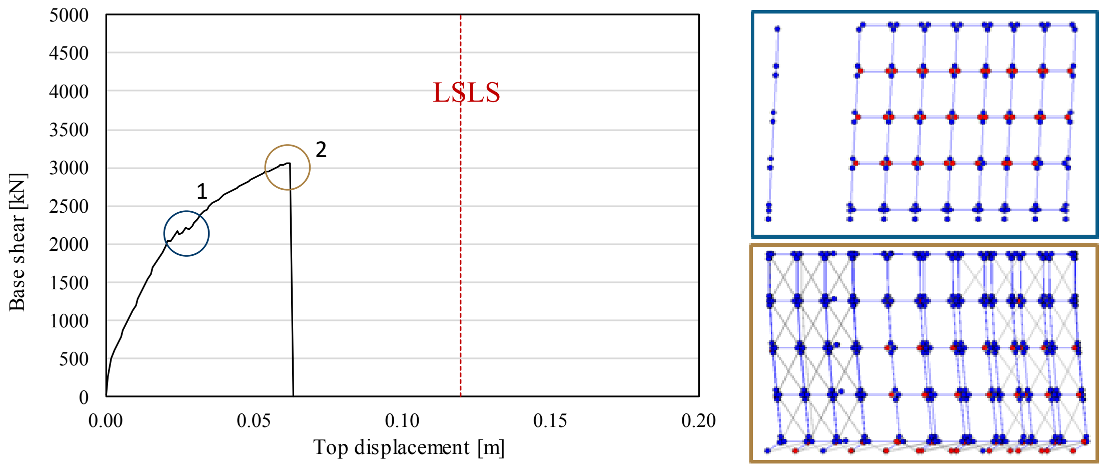

Figure 3. a) Capacity curve obtained from the PO analysis compared with the LSLS displacement demand b) main vulnerabilities of the existing building and collapse mechanisms (*bottom*).

3.3. Incremental rehabilitation strategy

3.3.1. Criteria. In order to remove the main vulnerabilities of the existing structure and to improve its seismic behavior without affecting its functionality, an incremental seismic rehabilitation strategy was adopted considering the following criteria [4]:

- Criteria for the structural retrofit:
  Basing on the structural priorities, a design parameter must be introduced to define the minimum intervention. Moreover, the new retrofitting structure should allow reaching adequate seismic performances, limiting damage, and repairing costs after a seismic event. For the reference case:
  1. The displacement demand target at the LSLS was set as displacement target for the minimum intervention in order to guarantee a minimum level of safety and avoid human losses in case of earthquake;
  2. To avoid severe damages on the existing building after a seismic event, a maximum inter-story drift equal to 0.5% was set as final displacement target.

- Criteria fostering environmental sustainability:
  New principles connected to an innovative Life Cycle Thinking (LCT) approach [4, 5] must be considered in the design of the incremental rehabilitation project. In the design phase, the whole Life Cycle of the retrofit solution must be considered thus accounting for the environmental impact of the retrofitting structure. Prefabricated, dry, easily demountable and reparable techniques should be fostered with respect to cast-in-place systems difficult to disassemble when damaged by major hazards or at the end of life.
- Criteria fostering social-economic sustainability:
  Basing on the use priorities of a scholastic structure, the incremental interventions should be completed exploiting the inactivity period of the scholastic building thus avoiding the disruption of the activities. Moreover, the incremental rehabilitation project must be economically feasible considering a low capital investment for each incremental rehabilitation step.

3.3.2. Incremental steps. An ISR plan was developed in three incremental steps to be realized during the inactivity summer period:

- Step 1: minimum intervention: elimination of the soft story mechanism at the basement by introducing steel bracings able to prevent the shear failure of the columns.
- Step 2: strengthening of the beams subjected to shear failure; with this step, the second main vulnerability of the building was solved.
- Step 3: introduction of new seismic resistant systems thus ensuring the displacement control, increasing the stiffness and the strength of the structure, consequently reducing the displacement demand and the damage on structural and non-structural elements. This intervention can be considered as a further step compared to the traditional seismic rehabilitation [10] to limit the damages on the building following a medium-high seismic event, significantly reducing the post-earthquake interventions and repair costs and impacts.

3.3.3. Results discussion. In Figure 4a the capacity curves obtained for each incremental rehabilitation step are plotted. The capacity curve obtained after the first step show that, by preventing the soft-story mechanism, the structure significantly increases its displacement capacity thus developing a ductile behavior. However, it is worth noting that, though the retrofitted building theoretically satisfies the displacement demand at the LSLS, the shear collapse of the beams in the frame F7 still occurs; for this reason, the second incremental step was needed.

The capacity curve obtained after the introduction of the second incremental rehabilitation step does not show significant improvements in terms of global strength and displacement capacity of the retrofitted building with respect to the capacity curve obtained after the first incremental rehabilitation step. However, with the second incremental rehabilitation step, any possible structural collapse was avoided thus resulting fully compliant to the current structural codes [10]. However, the high displacements and the high inter-story drift ratio obtained after the second step (Figure 4b) may lead to the failure of the non-structural components (such as the infill panels), or to the beam and column yielding, and to the flexural failure of some columns thus resulting in high repairing costs and in the existing building downtime after a seismic event.

To overcome the drawbacks of the traditional approach that account only for the LSLS in the retrofit design without considering the whole life cycle of the retrofitted structure, a third incremental step was introduced. New seismic-resistant shear wall systems composed of V-shaped reticular steel braces were arranged along the perimeter of the building and connected to each floor (Figure 5). This system, already applied for the structural retrofit of RC existing buildings [4-14], can be carried out from the outside thus reducing the impact of the intervention in terms of time and invasiveness. Moreover, the use of prefabricated and standardized elements significantly reduces the construction time also guaranteeing the reuse, the repair or the replacement of the structural elements (in accordance with the principles of LCT). In the reference case, two shear walls, for both the directions were introduced by adopting commercial steel tubular profile with diameter equal to 219.1 mm and thickness of 20 mm. In order to effectively control the behavior of the retrofitted structure, buckling of the shear wall elements had to be avoided. For this reason, elastoplastic dissipative systems in the retrofitting elements at the ground floor were introduced. The activation force of the elastoplastic system was calculated basing on the diagonal element features; more precisely, the axial limit force of each profile was considered [9]. At this point, the results show that, at the end of the three incremental rehabilitation steps, the LSLS displacement demand is reduced and satisfied; moreover, as shown in Figure 4b, the inter-story drift ratio at the third step is less than 0.5% drift thus avoiding the failure of the infill panels. In Figure 6, it is shown that the first incremental rehabilitation step (minimum intervention) features a significant increase of the safety level for low intervention costs; while, the third step requires a bigger investment to avoid damages on the structure. It is worth noting that the total amount of the structural retrofit solution is about 10% of the reconstruction costs (1400 €/m^2). In this preliminary evaluation, the demolition of the existing building and the waste disposal were not considered.

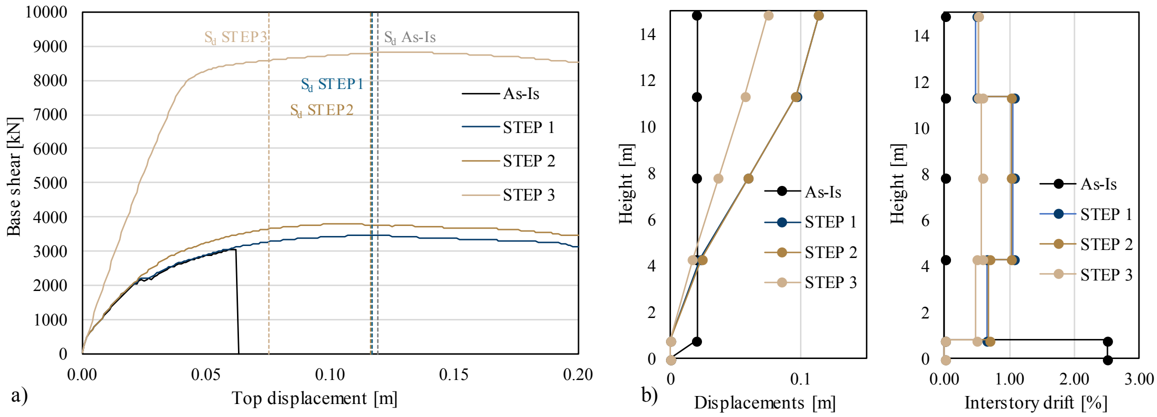

Figure 4. a) Comparison between the capacity curves obtained for each incremental step with the relative LSLS displacement demand; b) displacements and inter-story drift of each incremental step.

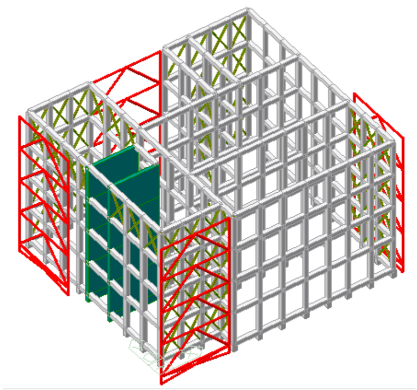

Figure 5. Finite Element Model of the retrofitted building at the third incremental step [9].

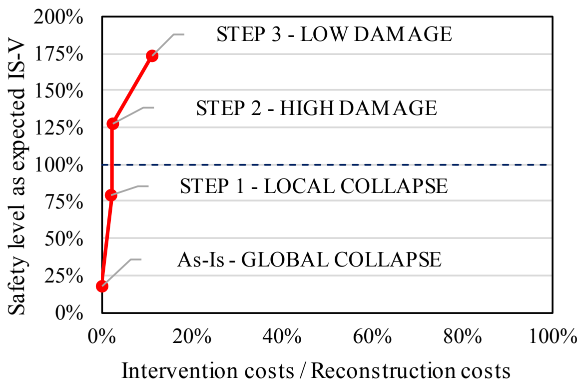

Figure 6. Safety level as expected by IS-V compared to the intervention costs expressed as a ratio of the reconstruction costs.

4. Concluding remarks

This work is part of an ongoing research on the integrated retrofit of the post-WWII RC buildings solving their main architectural, energy, and structural deficiencies, with the major aim of fostering a safe, resilient, and more sustainable society. Sustainability, safety and resilience cannot be pursued independently; sustainability must account for the hazard risk reduction of the existing building stock that results, in case of earthquake, unsafe and responsible of a significant impact on the environment in terms of waste production and CO_2 emission [15]. By addressing the LCT principle, in this paper, an incremental rehabilitation strategy is applied to spread construction costs and downtime over time thus resulting in a suitable strategy for the deep renovation of the existing building stock overcoming the major barriers to the renovation [1]. Additionally, the concept of minimum intervention has been introduced, with the aim to reach a minimum level of safety in the building heritage in a pretty short time. In this perspective, the first step of the incremental process should be conceived as the minimum intervention required to avoid heavy human and economic losses.

Incremental Seismic Rehabilitation (ISR) has been here applied to a school building where, based on structural priority and ISR principles, the best retrofit strategy has been determined. Through this case study, the benefits associated with the incremental rehabilitation approach have been shown, and the importance of the minimum intervention to make this strategy even more efficient has been highlighted.

In future research, a quantitative design parameter for the definition of the minimum intervention target would be investigated and a more accurate benefit/cost analysis would be carried out.

Acknowledgements
The authors gratefully acknowledge the Municipality of Brescia, particularly arch. Massimo Azzini and eng. Carlo Lazzaroni, for supporting our research and for providing all construction documents and diagnostic reports on the examined school.

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